

Perfect photon absorption in hybrid atom-optomechanical system

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Recently, the photon absorption attracts lots of interest and plays an important role in a variety of applications. Here, we propose a valuable scheme to investigate the perfect photon absorption in a hybrid atom-optomechanical system both under and beyond the low-excitation limit. The perfect photon absorption persists both in the linear atomic excitation regime and nonlinear atomic excitation regime, below the threshold of the optical bistability/multistability, respectively. We also show that the optical nonlinearity raised by the nonlinear optomechanical interaction and nonlinear atomic excitation can be overlap-added, there presents a perfect corresponding relation between perfect photon absorption and the optical multistability beyond the low-excitation limit, the optical bistability can be switched to the optical multistability by increasing the input intensity. The combination of the perfect photon absorption and optical bistability/multistability is useful for the photon switch application. We believe that this study will provide a possible design of an optical switch.

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I. INTRODUCTION

It is well known that photons as the carrier of the information, play an important role in quantum information and quantum communication. Recently, the photon absorption attracts a great deal of attention and has aroused widespread interest in recent studies [1–4]. Normally, the coherent perfect absorption corresponding to a certain frequency is determined by the intrinsic properties of the medium and the absorption of the input light was reported in Ref. [5, 6]. Recently, the coherent perfect photon absorption using path entanglement was also theoretically studied in Ref. [4] and then was demonstrated experimentally by Faccio et al [7]. The physical basis behind it is the destructive interference between the two input fields [6, 8]. It is shown that the perfect photon absorption has potential applications in optics communications and photonic devices including transducers, modulators, and optical switches and transistors [2, 11]. Therefore, some fundamental efforts have also been made on the achievement and applications of perfect photon absorption in various systems such as whispering-gallery-mode micro-resonators [9], the coupled atom-resonator-waveguide system [12], second harmonic generation [13], nanostructured graphene film [14] and strongly scattering media [15] and so on. In particular, the perfect photon absorption has also been studied not only in the cavity quantum electrodynamics [10, 11] but also in the cavity optomechanical system (COM) which enables the coupling between the mechanical modes and the optical field via the radiation pressure and attracts a lot of interest due to the rich physics [16, 17] and applications, e.g., ground state cooling [18], quantum coherent state transfer [19], pondero-

motive squeezing [20], quantum entanglement [21], optical Kerr nonlinearity [22], and gravitational wave physics [23, 24]. However, is the optomechanical coupling necessary in the perfect photon absorption in COM? or what's the essential role of the optomechanical coupling in the perfect photon absorption?

In this paper, we study the perfect photon absorption as well as the optical bistability/multistability in a hybrid atom-optomechanical system which couples to an ensemble of two-level atoms. Our results show that, the perfect photon absorption can be implemented in this system but always accompanied with the bistability or multistability of the output fields. While the optical intensity onset the bistability. In difference with Ref. [11], where the optical nonlinearity relies on the nonlinear atomic excitation, here the optical nonlinearity used is arisen from the radiation pressure interaction between moveable mirror and the cavity field, meanwhile the atomic ensemble linearly coupled with the cavity under the low excitation limit. Moreover, the photon absorption and optical bistability can be modified by the interference between the two input fields. In addition, we also employ both the atomic nonlinear excitation and nonlinear optomechanical interaction, the two nonlinearity can be overlap-add, both the intra-field and output field intensity can exhibit the optical multistability, the optical bistability switches to the optical multistability by increasing the input field intensity. Furthermore, the perfect absorption point also can be increased with the help of the optomechanical interaction. Finally, the demonstration of realizability within the current experimental technology on our scheme is also been discussed.

II. THE MODEL

As schematically shown in Fig. 1, we consider a typical hybrid atom-optomechanical system which consists of a

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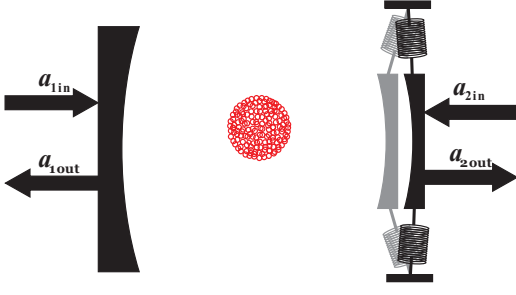


FIG. 1: (color online) Schematic setup. The hybrid atom-optomechanical system consists of a cloud of two level atoms in the cavity which is driven by two input light fields.

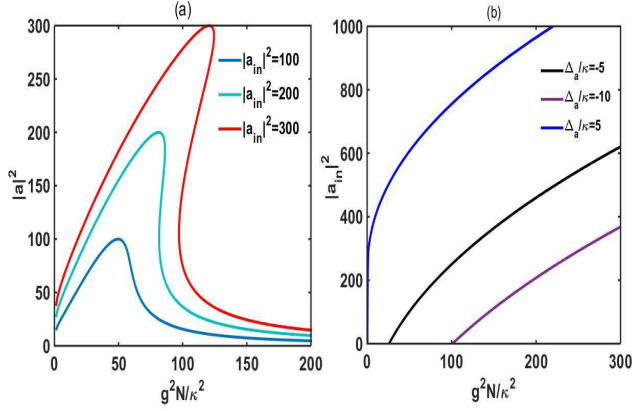


FIG. 2: (color online) Under the perfect absorption condition Eq. (12) and Eq. (13), (a) intra-cavity light intensity $|a|^2$ vs the fitting parameter g^2N with the different input light intensity $|a_{in}|^2$, the cavity-laser detuning $\Delta_a/\kappa = -5$. (b) the input intensity as a function of the fitting parameter g^2N with the different cavity-laser detuning. The other system parameters are $\Gamma/\kappa = 2$, $\omega_m/\kappa = 0.01$, $\gamma/\kappa = 0.1$, $g_0/\kappa = 0.1$, $\delta/\kappa = -\sqrt{g^2N/\kappa^2 - 1}$.

bare optical cavity coupled to a mechanical mode and N identical two-level atoms trapped in the cavity. The atomic transition frequency and the atomic line width are denoted by ω_e and Γ , respectively. In the rotating frame of the input laser frequency, the full Hamiltonian with regard for the driving and the dissipation, is given by (set $\hbar = 1$ hereafter)

$$H = \Delta_a a^\dagger a + \delta S^z + \omega_m b^\dagger b + g(aS^+ + a^\dagger S^-) - g_0 a^\dagger a(b^\dagger + b) + i\sqrt{2\kappa_1} a_{1in} a^\dagger + i\sqrt{2\kappa_2} a_{2in} a^\dagger - i\sqrt{2\kappa_1} a_{1in}^\dagger a - i\sqrt{2\kappa_2} a_{2in}^\dagger a, \quad (1)$$

where a denotes the cavity mode, and $S^z = \frac{1}{2} \sum_{i=1}^N (\sigma_i^+ \sigma_i^- - \sigma_i^- \sigma_i^+)$ and $S^\pm = \sum_{i=1}^N \sigma_i^\pm$ stand for the collective atomic operators with $\sigma_i^\pm = |e\rangle_i \langle g|$ representing the i th atomic raising and lowering operators. Here a_{1in} and a_{2in} are two input fields upon the cavity

with the same frequency ω_l . $\Delta_a = \omega_a - \omega_l$ is the laser detuning from the cavity mode and $\delta = \omega_e - \omega_l$ is the laser detuning from the atoms. Based on Hamiltonian (1) and the potential dissipation processes, one can derive the dynamics of the system from the Heisenberg equations of the operators. In the classical limit, namely, we drop the quantum fluctuations and replace the operators by their expectation values, one can obtain the equations of motion of the expectation values of the operators as follows.

$$\langle \dot{b} \rangle = -i\omega_m \langle b \rangle - \gamma \langle b \rangle - ig_0 \langle a^\dagger a \rangle, \quad (2)$$

$$\langle \dot{S}^- \rangle = -i\delta \langle S^- \rangle + 2ig \langle a S^z \rangle - \frac{\Gamma}{2} \langle S^- \rangle, \quad (3)$$

$$\langle \dot{S}^z \rangle = -\Gamma \langle S^z \rangle - ig \langle a S^+ \rangle + ig \langle a^\dagger S^- \rangle - \frac{N\Gamma}{2}, \quad (4)$$

$$\langle \dot{a} \rangle = -i\Delta_a \langle a \rangle - \kappa \langle a \rangle - ig \langle S^- \rangle - ig_0 \langle a \rangle (\langle b^\dagger \rangle + \langle b \rangle) + \sqrt{2\kappa_1} a_{1in} + \sqrt{2\kappa_2} a_{2in}, \quad (5)$$

where $\langle \dots \rangle$ represents the expectation value over the steady state. Combining above equations, we can solve the steady-state solution and obtain the intra-cavity field as

$$\langle a \rangle = \frac{\sqrt{2\kappa_1} a_{1in} + \sqrt{2\kappa_2} a_{2in}}{i\Delta_a + \kappa - \frac{N g^2}{2\langle S^z \rangle (\frac{\Gamma}{2} + i\delta)} - i\Xi |a|^2}, \quad (6)$$

where $\langle S^z \rangle = -\frac{N}{2(1 + \frac{2g^2|a|^2}{\Gamma^2 + \delta^2})}$ and $\Xi = \frac{2\omega_m g_0^2}{\gamma^2 + \omega_m^2}$. From Eq.

(6), one can easily get the intra-cavity intensity $|a|^2$ and, hence, obtain the properties of the photon absorption.

III. THE PHOTON ABSORPTION

A. Perfect photon absorption in the low-excitation limit

We first consider that the atomic ensemble is only in the low excitation regime. In this case, one can set $\langle S^z \rangle \approx -\frac{N}{2}$, so Eq. (6) can be reduced to

$$\langle a \rangle = \frac{\sqrt{2\kappa_1} a_{1in} + \sqrt{2\kappa_2} a_{2in}}{i\Delta_a + \kappa + \frac{g^2 N}{2 + i\delta} - i\Xi |a|^2}. \quad (7)$$

It is obvious that Eq. (7) includes the intra-cavity intensity $|a|^2$ and demonstrates the nonlinear dependence of the intra-cavity intensity. So the system may exhibit the optical bistability under the certain parameter range. In order to find the steady states of the two output light fields, one will have to consider the following input-output relation [28]

$$a_{1out} = \sqrt{2\kappa_1} a - a_{1in}, \quad (8)$$

$$a_{2out} = \sqrt{2\kappa_2 a} - a_{2in}. \quad (9)$$

One can assume that $a_{1in} = |a_{in}|$, $a_{2in} = e^{i\varphi} |a_{in}|$, where φ denotes the relative phase of the two opposite input fields. We also consider a symmetric cavity with $\kappa_1 = \kappa_2 = \frac{\kappa}{2}$, then the output intensity can be calculated as

$$\frac{|a_{1out}|^2}{|a_{in}|^2} = \left| \frac{\kappa(1 + e^{i\varphi})}{i\Delta_a + \kappa + \frac{g^2 N}{2 + i\delta} - i\Xi |a|^2} - 1 \right|^2, \quad (10)$$

$$\frac{|a_{2out}|^2}{|a_{in}|^2} = \left| \frac{\kappa(1 + e^{i\varphi})}{i\Delta_a + \kappa + \frac{g^2 N}{2 + i\delta} - i\Xi |a|^2} - e^{i\varphi} \right|^2. \quad (11)$$

Let us now focus our attention on how to realize the perfect photon absorption. The perfect photon absorption implies $a_{1out} = a_{2out} = 0$. One can find that if $\varphi \neq 2k\pi$, $k = 0, \pm 1, \pm 2, \dots$, the perfect photon absorption will not happen at any rate. So we restrict ourselves under the condition $\varphi = 0$ without loss of generality. Thus we can get two specific conditions for the perfect absorption:

$$\frac{\kappa}{\Gamma} = \frac{2g^2 N}{\Gamma^2 + 4\delta^2}, \quad (12)$$

$$\left(\frac{\kappa\Gamma}{2} + \Delta_a \delta - g^2 N\right) = \delta\Xi |a|^2. \quad (13)$$

In terms of Eqs. (12) and (13), we discuss some pertinent results about the perfect absorption and the bistable behaviors in the linear atomic excitation regime. By comparing with Ref. [10], one can find that the two perfect trapping conditions presented in Ref. [10] can be summarized by our Eq. (12). However, Eq. (13) is our distinguishing condition which is the result of the optomechanical interaction. The nonlinear interaction of the cavity-mechanical plays the dominant role in the optical bistability, and the hybrid atom-optomechanical system is driven into the bistable domain when the input light intensity is above the threshold for the onset of the optical bistability [29]. As shown in Eq. (7), the intra-cavity photon number is determined by both the atomic ensemble and the optomechanical parameters, thus we can harness them to control the optical bistable behavior and the photon absorption. For example, we can effectively control the parameters $g^2 N$ and the atomic frequency to match Eq. (12) and control the intra-cavity intensity to match Eq. (13). In Fig. 2 (a) and Fig. 2 (b) we display the intra-cavity intensity $|a|^2$ and the input light intensity $|a_{in}|^2$ as a function of the fitting parameter $g^2 N/\kappa^2$ under the condition of the perfect photon absorption. From Fig. 2 (a), one can see that the $|a|^2$ exhibits the bistability if the input intensity is large enough. In addition, even though the large input intensity can make the optomechanical system show the apparent bistability, this could require a relatively strong coupling $g^2 N/\kappa^2$, which is also illustrated by the monotonic relation between $|a_{in}|^2$ and

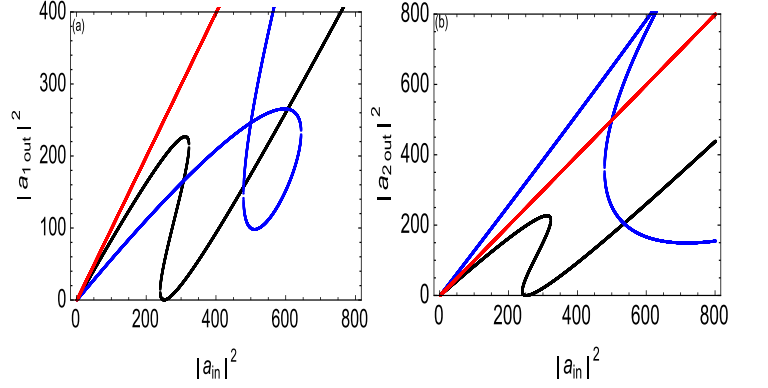


FIG. 3: (color online). Output light intensity $|a_{out}|^2$ as a function of input light intensity $|a_{in}|^2$ with the different relative phase φ . For this case, the two input lights have the same intensity $|a_{1in}|^2 = |a_{2in}|^2 = |a_{in}|^2$. The black line is for $\varphi = 0$, the blue curve stands for $\varphi = \pi/2$, the red line stands for $\varphi = \pi$. The other parameters are the same with Fig. 2.

$g^2 N/\kappa^2$ in Fig. 2 (b). It is also shown in Fig. 2 that the requirement of strong coupling can actually be compensated for by adding more atoms, or weakening the leakage κ or reducing the detuning Δ_a/κ . In addition, for nontrivial solutions, $|a_{in}| > 0$ requires that besides the condition given in Eq. (12), the perfect absorption should only occur in the following range of $g^2 N$, that is, (1) $g^2 N > \frac{\Delta_a^2 + \kappa\Gamma + \sqrt{\Delta_a^4 + 2\kappa\Gamma\Delta_a^2 - 4\Delta_a^2}}{2}$ for $\Delta_a < 0$; (2) $g^2 N > \frac{\kappa\Gamma}{2}$ for $\Delta_a > 0$. The numerical illustration of these ranges is given in Fig. 2 (b). Both the ranges imply the strong coupling $g^2 N$. In addition, one can also find that the large atomic frequency detuning $\Delta_a < 0$ will lead to the stronger coupling.

In what follows, we present the result for the two output light intensities $|a_{1out}|^2$ and $|a_{2out}|^2$ for the hybrid system in Fig. 3 (a) and Fig. 3 (b). One can find that the perfect photon absorption occurs solely at a particular input intensity $|a_{in}|^2 = \kappa\delta\Xi / (\frac{\kappa\Gamma}{2} + \Delta_a\delta - g^2 N)$ with the relative phase $\varphi = 2n\pi$, $n = 0, \pm 1, \pm 2, \dots$ (the black lines in the Fig. 3). Interestingly, we find that once the perfect absorption occurs, the output field intensity behaves the optical bistability where we can get three real distinct values for the output field intensity $|a_{out}|^2$ due to the nonlinear equation Eq. (7). Based on the Eq. (12) and Eq. (13), one can find that the perfect absorption can't occur if $g = 0$; Similarly, the optical bistability will vanish if $g_0 = 0$, even though the perfect absorption could still be present, which is consistent with Ref. [10]. In this sense, the perfect photon absorption mainly relies on the coupling between the atomic ensemble and the cavity, whereas the nonlinear optomechanical coupling plays the dominant role in the optical bistability [29]. It is different from Ref. [11] where the optical bistability relies on the nonlinear atomic excitation. In addition, the two output intensities can also be modified by the interference of the

two identical input lights, which can be shown by Fig. 3 (a) and (b). In Fig. 3, the blue lines correspond to $\varphi = \pi/2$ and the red lines correspond to $\varphi = \pi$. One can find that the bistability disappears ($\varphi = \pi$) or the system is driven to the complicated bistable domain ($\varphi = \pi/2$) by the effect of the relative phase, but the perfect absorption is absent. In other words, with φ changing from π to 0, the hybrid optomechanical system is driven from the monostable domain to the complicated bistable domain. During this procedure, one particular bistability results in the perfect absorption as shown in Fig. 3.

In Fig. 4, we plot the output light intensities versus $|a_{in}|^2$ for the different cavity-laser detunings. One can see that the different values of the atom-cavity detuning ($\Delta = \Delta_a - \delta$) don't take the edge off the perfect photon absorption and the optical bistability. The different Δ requires the different input light intensities to match the special conditions of the perfect absorption. With the small Δ , the system can be easily driven to the nonlinear regime and achieve the optical bistability, meanwhile, the perfect photon absorption can also happen with the relatively weak input light intensity.

Fig. 3 (a) and Fig. 3 (b) have shown that the relative phase has a deep influence on the photon absorption and the optical bistability. As mentioned above, the hybrid atom-optomechanical system could be out of the bistable domain and in particular, the perfect photon absorption does not occur due to the non-vanishing effect of the relative phase. To give an intuitive illustration, it is imperative to plot the output light intensity versus the relative phase φ . In Fig. 5 we plot the two output light intensities $|a_{1out}|^2$ and $|a_{2out}|^2$ with $|a_{1in}|^2 = |a_{in}|^2$, $|a_{2in}|^2 = e^{i\varphi} |a_{in}|^2$. One can see that the two output fields are not equal to each other except at some particular φ . These φ can be determined by solving Eq. (10) and Eq. (11) associated with Eq. (7), and thus one can have $\sin \varphi = 0$ or $\cos \varphi = c = (\kappa + \frac{g^2 N \Gamma}{2(\Gamma^2 + \delta^2)})^2 (\frac{\kappa \Gamma}{2} + \delta \Delta_a - g^2 N) / (2\kappa \Xi \delta_0^2 |a_{in}|^2) - 1$. It is obvious that at $\sin \varphi = 0$, the system demonstrates the perfect photon absorption, but at $\cos \varphi = c$ no perfect photon absorption is shown, even though the equal output light intensities have been present. In addition, some parameters including the driving, the detuning and so on could lead to $|c| > 1$, so $\cos \varphi = c$ can't hold any more. This case is illustrated in Fig. 5 (a) where the input intensity $|a_{in}|^2$ is set below the threshold of the bistable regime, hence $|a_{1out}|^2$ and $|a_{2out}|^2$ only show the mono-stability. On the contrary, when we adjust the parameters to satisfy the condition $|c| \leq 1$, the output light intensities could show the bistability, which is plotted in Fig. 5 (b). In this case, the phase can be used to manipulate the bistability and obtain various complicated bistable patterns in a certain region.

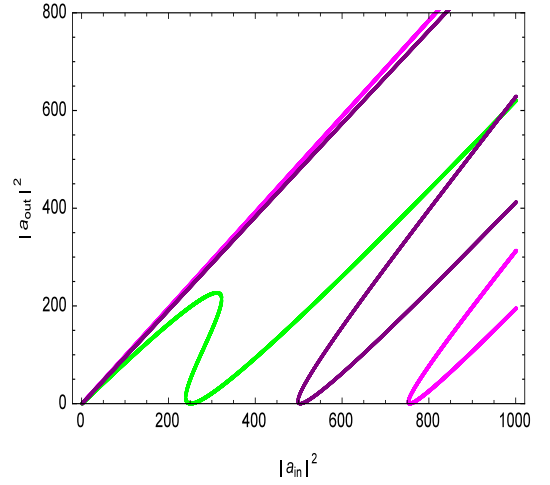


FIG. 4: (color online). The output intensity $|a_{out}|^2$ versus the variable $|a_{in}|^2$ with the different values of Δ_a/κ . The green, purple, magenta lines correspond to $\Delta_a/\kappa = -5$, $\Delta_a/\kappa = 0$, $\Delta_a/\kappa = 5$, respectively. The other parameters are same as Fig. 2.

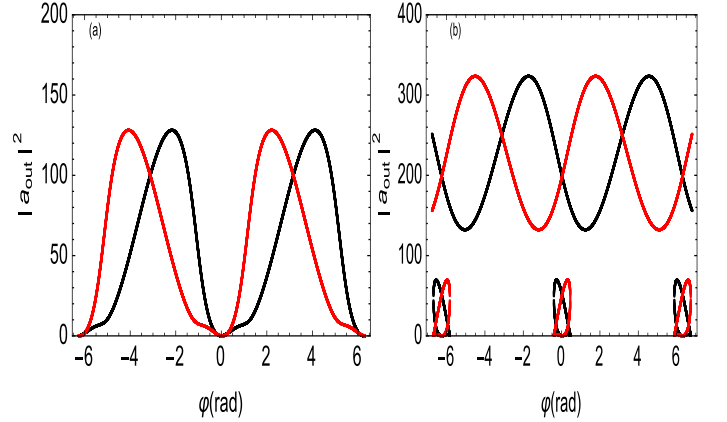


FIG. 5: (color online). The output intensity $|a_{out}|^2$ as a function of the relative φ . In (a), $|a_{in}|^2 = 100$, $\Delta_a/\kappa = -8$; in (b) $|a_{in}|^2 = 250$, $\Delta_a/\kappa = -5$. The red line is for $|a_{1out}|^2$ whereas the black line stands for $|a_{2out}|^2$. The other system parameters are same as Fig. 3.

B. Perfect photon absorption beyond the low-excitation limit

The consequences within the low-excitation limit have been studied in the previous section. Drowning on the findings above mentioned, a natural question will be arisen, thus, whether stronger and more robust nonlinearity can be achieved when the atomic assemble is driven into the nonlinear excitation regime? we expect that the nonlinearity caused by the atomic nonlinear excitation can be used to enhance the cavity optical nonlinearity, or has a positive effect on the perfect photon absorption in the hybrid atom-optomechanical system.

In the following, we will give the details on the coupling between the atomic ensemble and the cavity field in the nonlinear regime. Thus, in Eq. (6), we will have to directly employ $\langle S^z \rangle = -\frac{N}{2(1+\frac{2g^2|a|^2}{\Gamma^2+\delta^2})}$ instead of $\langle S^z \rangle =$

$-\frac{N}{2}$ to calculate the steady-state solution of the intra-cavity field from the Eq (2)- Eq (5). At this moment, the $\langle S^z \rangle$ is a function of the intra-cavity field intensity $|a|^2$ which satisfies the condition $|a|^2 > \frac{\Gamma^2}{4g^2}$. Therefore, two output optical intensity $|a_{1out}|'^2$ and $|a_{2out}|'^2$ can be given by

$$\frac{|a_{1out}|'^2}{|a_{in}|^2} = \left| \frac{\kappa(1+e^{i\varphi})}{i\Delta_a + \kappa + \frac{g^2N}{(\frac{\Gamma}{2}+i\delta)(1+\frac{2g^2|a|^2}{\Gamma^2+\delta^2})} - i\Xi|a|^2} - 1 \right|^2 \quad (14)$$

$$\frac{|a_{2out}|'^2}{|a_{in}|^2} = \left| \frac{\kappa(1+e^{i\varphi})}{i\Delta_a + \kappa + \frac{g^2N}{(\frac{\Gamma}{2}+i\delta)(1+\frac{2g^2|a|^2}{\Gamma^2+\delta^2})} - i\Xi|a|^2} - e^{i\varphi} \right|^2 \quad (15)$$

In order to show the perfect photon absorption, we would like to first list the corresponding conditions similar to the case in low-excitation limit. With $\phi = 0$, the conditions parallel with Eqs. (12) and (13) can be straightforwardly written as

$$\frac{\kappa\Gamma}{2} + \Delta_a\delta = \frac{g^2N}{1+\frac{2g^2|a|^2}{\Gamma^2+\delta^2}} + 2\delta\Xi|a|^2, \quad (16)$$

$$\frac{\Delta_a\Gamma}{2} - \kappa\delta = \frac{\Gamma\Xi}{2}|a|^2. \quad (17)$$

Compared with the perfect absorption conditions of the CQED system in Ref. [11], one can find that both the nonlinear cavity-mechanical coupling and the atom-cavity coupling have a certain influence on the perfect photon absorption in the nonlinear coupling regime.

In addition, from the Eq. (6), one can find that the intra-field intensity $|a|^2$ satisfies a quintic equation. Let $|a_{in}^1|^2 = |a_{in}^2|^2 = |a_{in}|^2$ ($\varphi = 0$) and $x := |a|^2$, the quintic equation reads

$$A_5x^5 + A_4x^4 + A_3x^3 + A_2x^2 + A_1x + A_0 = 0, \quad (18)$$

where

$$A_0 := -|\tilde{\Gamma}|^2|a_{in}|^2, \quad (19)$$

$$A_1 := (\tilde{\kappa}\tilde{\Gamma} + g^2N)(\tilde{\kappa}^*\tilde{\Gamma}^* + g^2N) - 2|\tilde{\Gamma}|^2\tilde{\delta}|a_{in}|^2, \quad (20)$$

$$A_2 := \tilde{\Gamma}\tilde{\delta}(\tilde{\kappa} - i\Xi)(\tilde{\kappa}^*\tilde{\Gamma}^* + g^2N) + \tilde{\Gamma}^*\tilde{\delta}(\tilde{\kappa}^* - \tilde{\omega}_m^*)(\tilde{\kappa}\tilde{\Gamma} + g^2N) - |\tilde{\Gamma}|^2\tilde{\delta}^2|a_{in}|^2, \quad (21)$$

$$A_3 := \left| \tilde{\Gamma}\tilde{\delta}(\tilde{\kappa} - i\Xi) \right|^2 - i\Xi\tilde{\Gamma}\tilde{\delta}(\tilde{\kappa}^*\tilde{\Gamma}^* + g^2N) + i\Xi\tilde{\Gamma}^*\tilde{\delta}(\tilde{\kappa}\tilde{\Gamma} + g^2N), \quad (22)$$

$$A_4 := i\Xi\tilde{\Gamma}^*\tilde{\delta}^*(-i\Xi - \tilde{\kappa}^*) - i\Xi\tilde{\Gamma}\tilde{\delta}(i\Xi - \tilde{\kappa}),$$

$$A_5 := \tilde{\delta}^2 \left| i\Xi\tilde{\Gamma} \right|^2, \quad (23)$$

$$\tilde{\Gamma} := i\delta + \frac{\Gamma}{2}, \quad (24)$$

$$\tilde{\kappa} := \kappa + i\Delta_a, \quad (25)$$

$$\tilde{\delta} := \frac{2g^2}{\frac{\Gamma^2}{4} + \delta^2}. \quad (26)$$

This quintic equation can not be analytically solved, so we only solve it numerically based on the Abel-Ruffini theorem [30, 31]. The numerical results are plotted in Fig. 6 which reveals a remarkable behavior of the intra-cavity intensity and the output field intensity. In Fig. 6 (a), we show the optical multistability and the perfect photon absorption as well as the relation between them. We observe that with the increasing of the input intensity, the output intensity demonstrates the monostability, bistability and multistability, respectively. One can notice that the onset of multistability requires a stronger input field intensity comparing with the linear excitation regime. This result suggests that the nonlinear coupling of atomic excitation could be employed to enhance the optical nonlinearity. It is especially interesting that the perfect photon absorption occurs at two particular input intensities: one is $|a_{in}|^2 = \frac{2g^2N\Gamma - \kappa\Gamma^2 - 4\kappa\delta^2}{8g^2}$ and the other is $|a_{in}|^2 = \frac{\kappa\Gamma\Delta_a - 2\kappa^2\delta}{\Gamma\Xi}$. This indicates that one can tune the input field intensity under the perfect absorption conditions (Eq.(16),Eq.(17)) to achieve the two perfect photon absorption points. Thus, the perfect photon absorption can be nonlinearly controlled by the input field intensity. Furthermore, one can find that the two perfect photon absorption points correspond to the optical bistability and multistability, respectively. This means that the two nonlinearities induced by the atom-cavity coupling and the cavity-mechanical coupling can be overlapped in a certain parameters regime. In other words, the nonlinear optomechanical interaction not only enhances the optical nonlinearity but also adds an additional perfect photon absorption point.

What's more, we would like to emphasize the main difference between the current scheme and the previous work [11]. The hybrid atom-optomechanical system provides a further understanding for the corresponding relation between the optical bistability/multistability and the perfect photon absorption. This can be shown by an example in Fig. 6 (b). The red line corresponds

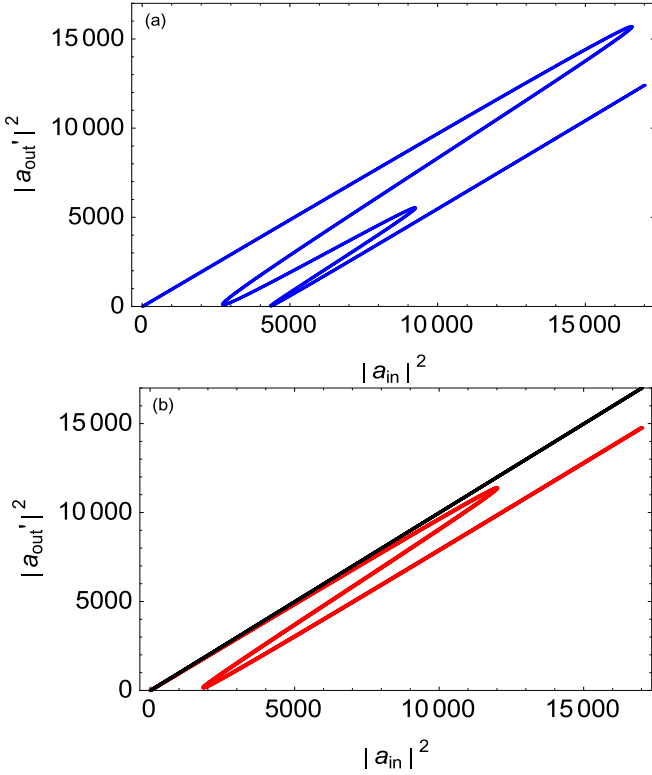


FIG. 6: (color online). Output light intensity $|a_{out}|^2$ as a function of input light intensity $|a_{in}|^2$ beyond the low-excitation limit. For this case, the two input lights have the same intensity $|a_{1in}|^2 = |a_{2in}|^2 = |a_{in}|^2$. In (a), $\Xi/\kappa = 0.0065$, in (b), the black line is for $g/\kappa = 0$, the red curve stands for $\Xi/\kappa = 0$ (absent of the optomechanical interaction). The other systems parameters are as follows: $\Delta_a/\kappa = 60$, $\delta/\kappa = 3$, $g^2 N/\kappa^2 = 240$.

to $g_0/\Gamma = 0$ (without the cavity-optomechanical coupling), whereas the black line corresponds to the standard optomechanical system without the atomic interaction. In Ref. [11], we find that the nonlinearity arises from the atomic nonlinear excitation regime which plays the dominate role in the optical bistability. In our case, when the atom-optomechanical coupling is absent, the hybrid optomechanical system is reduced to the CQED system, which is just consist with Ref. [11]. Once we consider the optomechanical coupling, one can find the optical nonlinearity has been enhanced and the perfect photon absorption occurs at two special input intensities $|a_{in}|^2$ as shown by the blue line in Fig. 6 (a). Similar to the case of the low-excitation limit, one can find that, if $g = 0$ (in absence of the atom ensemble), both the perfect photon absorption and the optical bistability of the output intensity disappear. This can be explained as follows. The output field intensity is given by $|a_{out}|'^2 = \left| \frac{\kappa - i\Delta_a + i\Xi|a|^2}{i\Delta_a + \kappa - i\Xi|a|^2} \right|^2 |a_{in}|^2 = |a_{in}|^2$ (here we set $\varphi = 0$) which implies that the output field intensity still behaves with the monostable properties, even though the

intra-cavity field is driven in the bistable regime. This is analogous to the optomechanically induced transparency (OMIT) [32, 33]. Equivalently, one can draw the same conclusion directly from the violation of the perfect absorption conditions given in Eq. (16) and Eq. (17).

Before the end, we briefly discuss the experimental feasibility of our scheme. Our proposal mainly depends on the parameters $g\sqrt{N}$, κ , Γ and g_0 . In experiment, $g\sqrt{N}/\Gamma = 20$ can be realized by the ultra cold atomic ensemble coupled with the cavity with the atomic half-linewidth $\Gamma = 2\pi \times 3M$ Hz [34–36]. In addition, the optomechanical parameters we used can be realized in various optomechanical systems, for example, $\omega_m/2\pi = 4.2 \times 10^4$ Hz, $g_0/2\pi = 6 \times 10^5$ Hz, $\kappa/2\pi = 6.6 \times 10^5$ Hz have been reported in Ref. [16], so the values of Ξ used in the main text can be easily achieved. To sum up, one can find that all the conditions required in this paper are realizable within the current experimental technology.

IV. CONCLUSIONS AND DISCUSSION

In summary, we have studied the optical response properties and the suppression of the output fields in the hybrid atom-optomechanical system with two identical input laser fields. It is shown that the perfect photon absorption is present in both the linear and nonlinear atomic excitation regimes. We find that in such a hybrid optomechanical system, the coupling with atomic ensemble is the sufficient and necessary condition for the perfect photon absorption, while the optomechanical coupling, enhancing the nonlinearity, forms the necessary condition for the optical bistability/multistability and especially induces an additional perfect absorption point in the nonlinear atomic excitation regime. As a result, we also find that the perfect photon absorption corresponds to the optical bistability/multistability. Furthermore, one can find that the interference of the two input fields can modify the photon absorption and optical bistability (multistability), so the bistability (multistability) and perfect absorption can be controlled by changing the relative phase between them, which provides a possible design of an optical switch. Finally, one should note that all the parameters employed in the numerical procedure are taken from the practical experiments, which ensures the practical feasibility in a variety of COM systems.

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